CLAIMS

We claim:

1. A method comprising:

(A) operating an internal combustion engine in a first mode comprising one of a diesel mode and a pilot ignited gaseous fuel mode; then

(B) operating said internal combustion engine in a second mode comprising the other of said diesel mode and said pilot ignited gaseous fuel mode; and

(C) during a transition period between said first and second modes, controlling engine operation based on at least one engine operating parameter other than total energy fuel content to achieve an at least substantially smooth transition between operating modes.

2. The method as recited in claim 1, wherein the at least substantially smooth transition is achieved by maintaining total engine torque at least substantially constant during the transition period.

3. The method as recited as claim 1, wherein the controlled engine operating parameter includes at least one of lambda and diesel fuel injection timing.

4. The method as recited in claim 3, wherein the transition is from pilot ignited gaseous fuel mode to diesel mode, the controlled engine operating parameter comprises diesel lambda, and the controlling step comprises controlling diesel lambda to be at a relatively high value at the beginning of the transition period and thereafter progressively reducing diesel lambda during the transition period.

5. The method as recited in claim 4, wherein the controlling step comprises

determining the actual gas lambda of the gaseous fuel at the beginning of the transition period,

determining a diesel lambda limit at the beginning of the transition period, and

adjusting diesel fuel delivery so as to maintain the actual diesel lambda at or above the diesel lambda limit.

6. The method as recited in claim 5, wherein the diesel lambda limit at the beginning of the transition period is determined by multiplying the determined actual gas lambda at the beginning of the transition period by a multiplying factor.

7. The method as recited in claim 5 or 6, further comprising, during the transition period, reducing the diesel lambda limit from the determined value at the beginning of the transition period to a final value that is at or near the diesel smoke limit.

8. The method as recited in claim 7, wherein the reducing step comprises incrementally reducing the diesel lambda limit using a predetermined schedule that is dependent on at least one of engine speed and time.

9. The method as recited in one or more of claims 6 - 8, wherein the step of determining the diesel lambda limit at the beginning of the transition period comprises solving the following equation:

$$\lambda_{diesel\text{-}limit} = \frac{x\left(SAFR_{diesel}\right) + \lambda_{gas}\left(SAFR_{gas}\right)}{HVR\left(SAFR_{diesel}\right)}$$

where:

x = the prevailing pilot diesel mass fraction,

$SAFR_{diesel}$ = the stoichiometric air-fuel ratio for the diesel fuel,

λ_{gas} = the determined actual gas lambda at the beginning of the transition period,

$SAFR_{gas}$ = the stoichiometric air-fuel ratio for the gaseous fuel, and

HVR = the prevailing mass ratio of the diesel fuel to the total fuel charge on an equivalent total fuel energy basis.

10. The method as recited in claim 4, wherein the transition is from diesel mode to pilot ignited gaseous fuel mode, and wherein the controlling step comprises

determining the actual gas lambda of the gaseous fuel at the beginning of the transition period,

determining a gas lambda-rich limit for prevailing engine operating conditions,

comparing the determined actual gas lambda to the gas lambda-rich limit, and

operating the engine in diesel mode if the determined gas lambda is less than the determined gas lambda-rich limit.

11. The method as recited in claim 10, further comprising determining the gas lambda-rich limit based at least in part on at least one of manifold absolute pressure and air charge temperature.

12. The method as recited in claim 3, wherein the controlled engine operating parameter is ignition timing.

13. The method as recited in claim 12, wherein the controlling step comprises

selecting a desired ignition timing for the second mode, the desired ignition timing for the second mode being different than the existing ignition timing for the first mode, and

adjusting ignition timing incrementally over a plurality of engine operating cycles until the actual ignition timing at least approximately equals the desired ignition timing.

14. The method as recited in any of claims 1-13, wherein said engine is a dual fuel engine capable of operating only in the diesel mode and the pilot ignited gaseous fuel mode.

15. The method as recited in any of claims 1-14, further comprising controlling fuel supply to maintain total fuel energy content at least substantially constant during the transition period.

16. A method comprising:

(A) operating a dual fuel internal combustion engine in a first mode comprising one of a diesel mode and a pilot ignited gaseous fuel mode; then

(B) operating said internal combustion engine in a second mode comprising the other of said diesel mode and said pilot ignited gaseous fuel mode; and

(C) during a transition period between said first and second modes, controlling engine operation based on multiple engine parameters including lambda to achieve an at least substantially smooth transition between operating modes by maintaining total engine torque at least substantially constant.

17. The method as recited in claim 16, wherein the transition is from pilot ignited gaseous fuel mode to diesel mode, a controlled engine operating parameter comprises diesel lambda, and the controlling step comprises controlling diesel lambda to be at a relatively high value at the beginning of the transition period and thereafter reducing diesel lambda toward a smoke limit by the end of the transition period.

18. The method as recited in claim 17, further comprising determining a diesel lambda limit at the beginning of the transition period using the following equation:

$$\lambda_{diesel\text{-}limit} = \frac{x\left(SAFR_{diesel}\right) + \lambda_{gas}\left(SAFR_{gas}\right)}{HVR\left(SAFR_{diesel}\right)}$$

where:

x = the prevailing diesel fuel mass fraction,

$SAFR_{diesel}$ = the stoichiometric air-fuel ratio for the diesel fuel,

λ_{gas} = the determined actual gas lambda at the beginning of the transition period,

$SAFR_{gas}$ = the stoichiometric air-fuel ratio for the gaseous fuel, and

HVR = the prevailing mass ratio of the diesel fuel to the total fuel charge on an equivalent total fuel energy basis.

19. The method as recited in claim 16, wherein the transition is from diesel mode to pilot ignited gaseous fuel mode, a controlled engine operating parameter comprises gas lambda, and the controlling step comprises:

determining the actual gas lambda of the gaseous fuel at the beginning of the transition period,

determining a gas lambda-rich limit for prevailing engine operating conditions,

comparing the determined gas lambda to the gas lambda-rich limit, and

operating the engine in diesel mode if the determined gas lambda is less than the determined gas lambda-rich limit.

20. An internal combustion engine comprising:

(A) at least one cylinder;

(B) a source of diesel fuel configured to supply a liquid fuel to said cylinder;

(C) a source of a gaseous fuel configured to supply a gaseous fuel to said cylinder; and

(D) a controller that is coupled to said diesel fuel source and said gaseous fuel source and that controls said sources to selectively

(1) supply fuel to said engine in a first mode comprising one of a diesel mode and a pilot ignited gaseous fuel mode, then

(2) supply fuel to said engine in a second mode comprising the other of said diesel mode and said pilot ignited gaseous fuel mode, and

(3) during a transition period between said first and second modes, control engine operation based on at least one engine operating parameter other than total energy fuel content to achieve an at least substantially smooth transition between operating modes.

21. The engine as recited as claim 20, wherein the controlled engine operating parameter includes at least one of lambda and liquid fuel injection timing.

22. The engine as recited in claim 21, wherein, during a transition from pilot ignited gaseous fuel mode to diesel mode, the controlled engine operating parameter comprises

diesel lambda, and the controller is operable to set diesel lambda at a relatively high value at the beginning of the transition period and thereafter reduce diesel lambda during the transition period.

23. The engine as recited in claim 22, wherein, during the transition from pilot ignited gaseous fuel mode to diesel mode, the controller is operable to

determine the actual gas lambda of the gaseous fuel at the beginning of the transition period,

determine a diesel lambda limit, and

adjust diesel fuel delivery to maintain the actual diesel lambda at or above the diesel lambda limit.

24. The engine as recited in claim 23, wherein, at the beginning of the transition period, the controller is operable to determine the diesel lambda limit by multiplying the determined actual gas lambda by a multiplying factor.

25. The engine as recited in claim 23 or 24, wherein the controller is further operable, during the transition from pilot ignited gaseous fuel mode to diesel mode, to reduce the diesel lambda limit from the determined value at the beginning of the transition period to a final value that is at or near the diesel smoke limit.

26. The engine as recited in claim 25, wherein the controller is operable to reduce the determined diesel lambda limit using a predetermined schedule that is dependent on at least one of engine speed and time.

27. The engine as recited in any of claims 23-26, wherein the controller is operable to determine the diesel lambda limit at the beginning of the transition period by solving the following equation for the determined gas lambda:

$$\lambda_{diesel\text{-}limit} = \frac{x\left(SAFR_{diesel}\right) + \lambda_{gas}\left(SAFR_{gas}\right)}{HVR\left(SAFR_{diesel}\right)}$$

where:

x = the prevailing diesel fuel mass fraction,

$SAFR_{diesel}$ = the stoichiometric air-fuel ratio for the diesel fuel,

λ_{gas} = the determined gas lambda at the beginning of the transition period,

$SAFR_{gas}$ = the stoichiometric air-fuel ratio for the gaseous fuel, and

HVR = the prevailing mass ratio of the liquid fuel to the total fuel charge on an equivalent total fuel energy basis.

28. The engine as recited in claim 21, wherein, during a transition from diesel mode to pilot ignited gaseous fuel mode, the controller is operable to

determine the actual gas lambda of the gaseous fuel at the beginning of the transition period,

determine a gas lambda-rich limit for prevailing engine operating conditions,

compare the determined actual gas lambda to the gas lambda limit, and

operate the engine in diesel mode if the determined gas lambda is less than the determined gas lambda-rich limit.

29. The engine as recited in claim 28, wherein the controller is operable to determine the gas lambda-rich limit based at least in part on at least one of manifold absolute pressure and air charge temperature.

30. The engine as recited in claim 21, wherein, during the transition period, the controller is operable to

select a desired ignition timing for the second mode, the desired ignition timing for the second mode being different than the existing ignition timing for the first mode,

adjust ignition timing incrementally over a plurality of engine operating cycles until the actual ignition timing at least approximately equals the desired ignition timing.

31. The engine as recited in any of claims 20-30, wherein the engine is a dual fuel engine capable of operating only in the diesel mode and the pilot ignited gaseous fuel mode.

32. The engine as recited in any of claims 20-31, wherein the controller is further operable to control fuel supply to maintain total fuel energy at least substantially constant during the transition period.